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Considerations and Recommendations Regarding the Use of Judgmental Sampling in Soil Investigations

Discussion Draft Report

Presented to:

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RTI INTERNATIONAL

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Acknowledgments

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Dr. Richard O. Gilbert, a discussion panelist for the Symposium session, provided helpful peer review comments during the development of the draft report. Dr. Gilbert, who is recently retired from Battelle Memorial Institute's Pacific Northwest Laboratory Division, is participating as an independent consultant.

1. INTRODUCTION

This paper explores a number of key issues surrounding the selection and use of judgmental sampling for investigating potentially contaminated soils. The issues considered include:

- When is judgmental sampling an appropriate and defensible sampling approach for contaminated soil investigations?
- What limitations and caveats must be acknowledged when using judgmental sampling and the resulting data?
- When a judgmental sampling approach is selected, what criteria can be used to assure it is implemented properly?
- What kinds of data analysis methods are appropriate when the data were generated through a judgmental sampling design?
- If judgmental sampling is not appropriate, what are some cost-effective statistical sampling designs that may satisfy the project's objectives?

The use of professional judgment is always a necessary and important part of a site investigation. The issue that this paper explores is *how* judgment can be applied appropriately to the design of a sampling plan. If we want to generate accurate and meaningful environmental measurements, we must apply knowledge and professional judgment from a broad range of scientific and engineering disciplines to a complex chain of events, such as identification of contaminants of concern, delineation of spatial boundaries for the investigation, selection of field sampling instruments, application of analytical methods, and so on. One of the critical steps in this chain of events is determining exactly which locations at a site will be sampled. In judgmental sampling, the sampling points are determined by qualified professionals who direct the sampling crews to sample at specific locations and depths, based on field observations, prior information about the site, analysis of the conceptual site model, and so on. In statistical sampling, the specific sampling points are determined through a random selection process within specific boundaries that are established using prior information and analysis similar to that employed in judgmental sampling.

The selection of sampling locations takes on great importance due to the fact that a relatively small quantity of soil from each sampling location will be analyzed and relied upon to represent conditions at the site. In essence, the representativeness of the data–and therefore its meaning to the decision maker–will be greatly influenced by the approach used to select sampling locations. For example, if judgmental sampling is used to take samples at those locations on the site where contamination is thought to be highest, then the data will represent "worst case" conditions. If statistical sampling is used to take samples over a large area of the site, the data may represent "average" conditions within that area. The reliability of the investigation–such as the ability to replicate results or characterize the uncertainty in estimates of site conditions–will be influenced by the appropriateness of the methods used to select sampling locations, the transparency of those methods (i.e., how well the rationale is explained and assumptions documented), as well as the number of samples collected. Therefore, the issue of how one chooses sampling locations is of critical importance in developing and evaluating sampling and analysis plans for site investigations of potentially contaminated soils.

1.6 Definitions

Before proceeding further with the discussion, we clarify the terms and definitions that are used in this document (see Table 1).

Table 1. Definitions

Term used in this document	Definition	Synonyms
judgmental sampling	A non-probability based method for choosing locations for collecting samples, based on expert opinion, professional judgement, or existing information without the use of any randomization process. Judgmental sampling relies on explicit or implicit criteria that relate the sampling objectives and methods to a conceptual model of site conditions or processes.	authoritative sampling; subjective sampling; directed sampling
statistical sampling	A probability-based method for choosing locations for collecting samples. This would include all sampling designs for which there is a known probability for the selection of any point or unit to be measured or observed. Statistical sampling usually involves a randomized selection scheme, and can involve grid sampling, stratified sampling, or compositing.	probability sampling
haphazard sampling	A non-probability based method for choosing locations for collecting samples without consideration of science- or engineering-based sampling objectives or conceptual site models. Haphazard sampling is the equivalent of selecting sampling locations as an afterthought, or without any systematic planning. Haphazard sampling is to be avoided.	convenience sampling
professional judgment	Use of prior knowledge to improve a sampling design. Professional judgement is clearly used in judgmental sampling but can also be used to improve statistical sampling designs, for example, in defining the boundaries of sampling strata.	expert opinion, best practices

1.2 Description of the Problem

Site investigations conducted under the Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response, and Compensation, and Liability Act (CERCLA, or "Superfund"), Brownfields, and other federal, state and local programs usually require the collection of measurement data to support decision making about the site. (In this paper, we focus on soil investigations, although many of the concepts can be applied to other environmental media.) Environmental measurements are expensive, so the sampling approach should be designed to obtain useful and sufficiently accurate information at a minimum cost (or, alternately, maximize the usefulness and accuracy of the information within a given budget). Site decisions must be defensible to the public and in court, hence the methods for obtaining data must be transparent, logical, and technically correct. Site investigations can be complex, and some level of uncertainty in the results is unavoidable. Consequently, the decision maker should be willing to specify the level of uncertainty that he or she can tolerate. Often this tolerable level of uncertainty is expressed as a desired level of statistical confidence, tolerable probabilities of committing decision errors, or some other type of performance criterion for the quality of the decision or estimate. The goal of the sampling design is to produce the type, quality, and quantity of data necessary to support the decision with the desired level of confidence in the results.

Judgmental sampling is commonly used to investigate soil contamination at a site. The ability to directly choose sampling locations in areas of interest provides a high degree of control over sampling costs. Judgmental sampling is appropriate for many situations, particularly in the early stages of site investigations, or when "worst case" screening decisions are being made. However, there are limitations on the proper use of data generated through judgmental sampling, and those limitations may not be consistent with the sampling objectives for certain key site decisions. For example, site decisions that are based on site-specific assessments of risk to human health from long-term exposure to contaminants require reliable estimates of the level of contamination averaged over relatively large areas, such as a half acre or more. In these situations, judgmental sampling may introduce bias and therefore limit the usefulness of the resulting data, perhaps jeopardizing the defensibility of subsequent risk-based decisions. Instead, statistical sampling designs often offer the best approach to support formal risk-based decision making because statistical sampling provides an objective and scientifically defensible method for obtaining unbiased, efficient estimates of site conditions. Statistical sampling also allows the level of uncertainty to be characterized quantitatively using standard methods, so that it is relatively straightforward to assess whether the decision maker's desired level of confidence or tolerable decision error rates were achieved.

Ultimately, judgmental and statistical sampling both have important roles in developing sampling and analysis plans over the life cycle of a site investigation and remediation project. Moreover, statistical sampling techniques can improve the validity of judgmental sampling, and professional judgment is crucial to the development of sound statistical sampling designs, as will be explained in this report. Table 2 summarizes some of the strengths and limitations of statistical versus judgmental sampling. Additional background information comparing judgmental and statistical sampling is provided in Appendix A.

Table 2. Comparison of Strengths and Limitations of Statistical Versus Judgmental Sampling

	Statistical Sampling	Judgmental Sampling
Strengths	• Supports valid inference to population or area of concern • Supports quantitative estimates of uncertainty, variance • Can determine if the results meet the acceptable limits on uncertainty required for the decision • "Randomness" is insurance that you haven't missed anything that was not expected based on the conceptual site model	• May be easier to explain how sampling locations were chosen (when well documented) • Can avoid areas you are not concerned about • Can sample more intensely in areas you are concerned about • Greater control over sampling costs • May be perceived to result in better coverage in areas of concern, which may make approach more appealing to managers
Limitations	• For more complex designs, may be harder to explain how specific sampling locations were chosen • May be concern that locations will be chosen that don't seem to make sense for the project (especially if design developed with insufficient input from site experts) • Little perceived control over sampling costs • Benefits of additional sampling costs (over judgmental sampling) may be harder to justify	• Difficult to make defensible inference beyond the immediate area sampled • Cannot use resulting data to calculate valid unbiased estimates of variance or uncertainty • Cannot determine if the results meet the tolerable limits on uncertainty required for the decision • Subjectivity more vulnerable to challenge • Cannot make statements about the probability that a hot spot was missed
Most Likely to Apply When...	• Site conditions are heterogeneous or unknown • Conceptual site model is uncertain • Prior information is limited or uncertain • Sampling objective is to obtain an unbiased estimate of a population parameter (e.g., mean contaminant concentration) over an area, or to detect a hot spot of given size with specified probability • The data analysis objective is to test a hypothesis using statistical methods, characterize the uncertainty of an estimate of a population parameter, or calculate the probability of making a decision error	• Site conditions are homogeneous • Conceptual site model is accurate and reliable • Prior information is accurate, detailed, and reliable • Sampling objective is to characterize a point or pattern, such as a contamination boundary • Decision rule involves "worst case" screening, and visual cues or site knowledge supports reliable search for "worst" locations

1.3 Objectives of This Paper

The goal of this paper is to provide information and guidance to those who prepare sampling and analysis plans or review sampling and analysis plans prepared by others. This paper provides information on the appropriate and inappropriate uses of judgmental sampling to help guide sampling design and to assist those who review and comment on sampling plans proposing the use of judgmental sampling. This paper describes the sampling objectives and situations for which judgmental sampling is appropriate and defensible. In addition, this paper provides explanations of why judgmental sampling is not appropriate in other cases, so that the reviewer has the supporting arguments to make his or her perspective understood.

This paper also is intended to serve as a starting point for a discussion panel session at the Midwest States Risk Assessment Symposium, July 24-26, 2002, organized by the Indiana Department of Environmental Management (IDEM). IDEM may use the findings in this paper and the results of the discussion panel session to develop further guidance on the application and use of judgmental sampling.

1.4 Technical Approach

IDEM contracted with RTI International[1] to coordinate the work of an expert panel to develop these recommendations. RTI's project leader identified other RTI staff and recruited experts from the U.S. Environmental Protection Agency (USEPA) and academia to participate on the expert panel (see Table 3).

Table 3. Expert Panel Participants

Name	Affiliation
Malcolm J. Bertoni, M.S., C.Q.M.(Chair)	RTI International
Kara Morgan, Ph.D.	RTI International
Prof. Mitchell Small, Ph.D.	Carnegie Mellon University
Andrew Stahl, M.S., P.G.	RTI International
John Warren, Ph.D.	U.S. EPA

RTI conducted a literature search to identify publications addressing the use of judgmental sampling, which yielded minimal useful results (see Appendix B). Expert panel members consulted with professional colleagues to identify sources of information and best

[1] RTI International is a trade name for Research Triangle Institute (RTI)

practices. The current report represents a synthesis of the expert panel's deliberations based on our assessment of the current state of science and professional best practices. The recommendations below for planning and evaluating judgmental sampling approaches represent a discussion draft that is intended to serve as a starting point for deliberation and refinement. The development of additional detailed guidance on the numerous operational considerations that arise when applying judgmental sampling in an appropriate situation would require further work.

2. RECOMMENDED PLANNING CONSIDERATIONS FOR JUDGMENTAL SAMPLING

The design of a sampling and analysis plan should begin with the use of a systematic planning process that includes the elements described in the USEPA Quality Manual (USEPA 2000d). The Data Quality Objectives (DQO) process is one such systematic planning approach recommended by the USEPA and IDEM (see IDEM 2001, USEPA 2000a, USEPA 2000b, and USEPA 1993 for detailed information about the DQO process). The recommended planning considerations described in this section represent a subset of key activities in the DQO process that have been tailored to address judgmental sampling. The planning considerations are:

- determining the sampling objectives;
- selecting a sampling approach;
- specifying performance criteria; and
- developing the Sampling and Analysis Plan.

2.1 Determining the Sampling Objectives

Perhaps the most critical aspect of designing a sampling plan is deciding exactly what the sampling objectives are, given the site decision to be made. The use of a systematic planning process helps ensure that the sampling objectives are based on sound analysis that takes into account all relevant scientific, engineering, legal, and managerial issues that may influence the decision. In particular, the USEPA's DQO process was developed to help decision makers clarify why data are needed, how data will be used, and how precise the results need to be to achieve the decision maker's desired level of confidence in the decision. The USEPA Quality Staff have developed a guidance document that applies the general 7 steps of the DQO process more specifically to hazardous waste site investigations, as shown in Figure 1 (USEPA 2000b). This process has been used successfully to plan many site investigations. The guidance is available for free download at www.epa.gov/quality, and the details of the process will not be repeated here. However, this section does discuss some important considerations regarding the identification of sampling objectives that may be consistent with a judgmental sampling approach.

One of the key tasks of the planning team is to identify the target population for the sampling effort. The target population represents the focus of the decision, in that the objective of the sampling design is to obtain data that will accurately represent the characteristics of interest in the target population, such as the distribution of contaminants (the characteristic) in surface soil over a defined geographic area and time period (the target population to be studied). The planning team identifies the target population and the characteristics of interest during DQO process Step 4, "Define the Study Boundaries." One additional planning decision needs to be made before the sampling objective can be fully specified: the population *parameter* of interest. This is the mathematical interpretation of the term "parameter" in the sense that it describes how the information about the target population will be summarized. For example, the team must clarify if they want to make a site decision based on a measure of central tendency (such as a mean or median) versus an extreme value (such as a 99th percentile). The population parameter of interest is specified in DQO process Step 5, "Develop a Decision Rule." By the time the planning team has completed the decision rule in Step 5, they should know what the sampling objective is, which will allow them to decide whether a judgmental or statistical sampling approach will be used.

<u>THE DATA QUALITY OBJECTIVES PROCESS</u>

1. STATE THE PROBLEM
Summarize the contamination problem that will require new environmental data, and identify the resources available to resolve the problem; develop conceptual site model.

2. IDENTIFY THE DECISION
Identify the decision that requires new environmental data to address the contamination problem.

3. IDENTIFY INPUTS TO THE DECISION
Identify the information needed to support the decision and specify which inputs require new environmental measurements.

4. DEFINE THE STUDY BOUNDARIES
Specify the spatial and temporal aspects of the environmental media that the data must represent to support the decision.

5. DEVELOP A DECISION RULE
Develop a logical "if. . . then. . ." statement that defines the conditions that would cause the decision maker to choose among alternative actions.

6. SPECIFY LIMITS ON DECISION ERRORS
Specify the decision maker's acceptable limits on decision errors, which are used to establish performance goals for limiting uncertainty in the data.

7. OPTIMIZE THE DESIGN FOR OBTAINING DATA
Identify the most resource-effective sampling and analysis design for generating data that are expected to satisfy the DQOs.

Figure 1. The DQO Process.

For the purposes of this paper, all soil sampling objectives are broken down into three types: characterizing conditions at a suspect location or point, characterizing conditions over a given area, and characterizing a pattern of soil conditions, such as the delineation of the boundary where soil contamination exceeds an unacceptable limit (e.g., a closure level). Table 4 shows a number of typical decisions at various stages of a project life cycle, and how those decisions relate to these three types of sampling objectives. The decision processes for selecting a sampling approach (i.e., deciding if judgmental sampling might be appropriate in these types of situations) are discussed in the next section.

Table 4. Examples of Site Decisions and Corresponding Sampling Objectives

Stage in Site Life Cycle (per USEPA 2000b)	Site Decision/Intended Use of Data	Sampling Objective is to Characterize...
Initial Site Assessment	Determine whether a contaminant release has occurred	a point
	Identify all contaminants of concern	a point or pattern
Site Investigation	Determine whether the lifetime risk of cancer incidence exceeds 10^{-5}	an area
	Identify the existence/location of hot spots	a point
Evaluation of Remedial Alternatives	Delineate the extent of unacceptable contamination	a pattern
	Estimate the volume of material to be remediated	a volume
Remedy Selection/ Implementation	Determine whether the remediation technology is performing effectively enough to achieve goals	rate of change at a point or over an area
	Determine whether cleanup goals have been attained	an area

2.2 Selecting a Sampling Approach

At this point in the planning process, the planning team has specified the boundaries of the investigation (DQO process step 4), developed a decision rule (DQO process step 5), and identified a corresponding sampling objective. Before moving to step 6 of the DQO process, where the decision maker specifies tolerable limits on decision errors, the planning team should consider whether a judgmental or statistical sampling approach will be used. Figures 2, 3, and 4 in the following subsections show three decision diagrams, one for each type of sampling objective, which the planning team can use to help decide whether judgmental or statistical sampling is appropriate.

2.2.1 Characterizing Conditions at a Point or Suspect Location

Figure 2 shows the decision process for a selecting a sampling approach when the sampling objective is to determine the contaminant concentrations at a known location or point. This type of objective would be relevant, for example, if there was a small area of contamination from a known or suspected spill or leak that needs to be evaluated to confirm the release. Another example would be when the objective is to evaluate a location believed to represent the point of greatest contamination to determine if the contaminant concentration exceeds a threshold that would trigger some action or necessitate further evaluation. The first branch asks if the contaminant can be readily identified in the field; if so, then the field screening method can be applied using either judgmental or systematic grid sampling. The results from the field screening can then be used to guide judgmental sampling of specific points of interest using standard analytical methods for confirmation. If a convenient field screening method is not available, then the selection of a sampling approach hinges on the quality of information known at that time regarding the release mechanism and site conditions, as well as the confidence the project team has in the accuracy of its conceptual site model. If little prior information is available, or the conceptual site model is highly uncertain, then a statistical approach may be

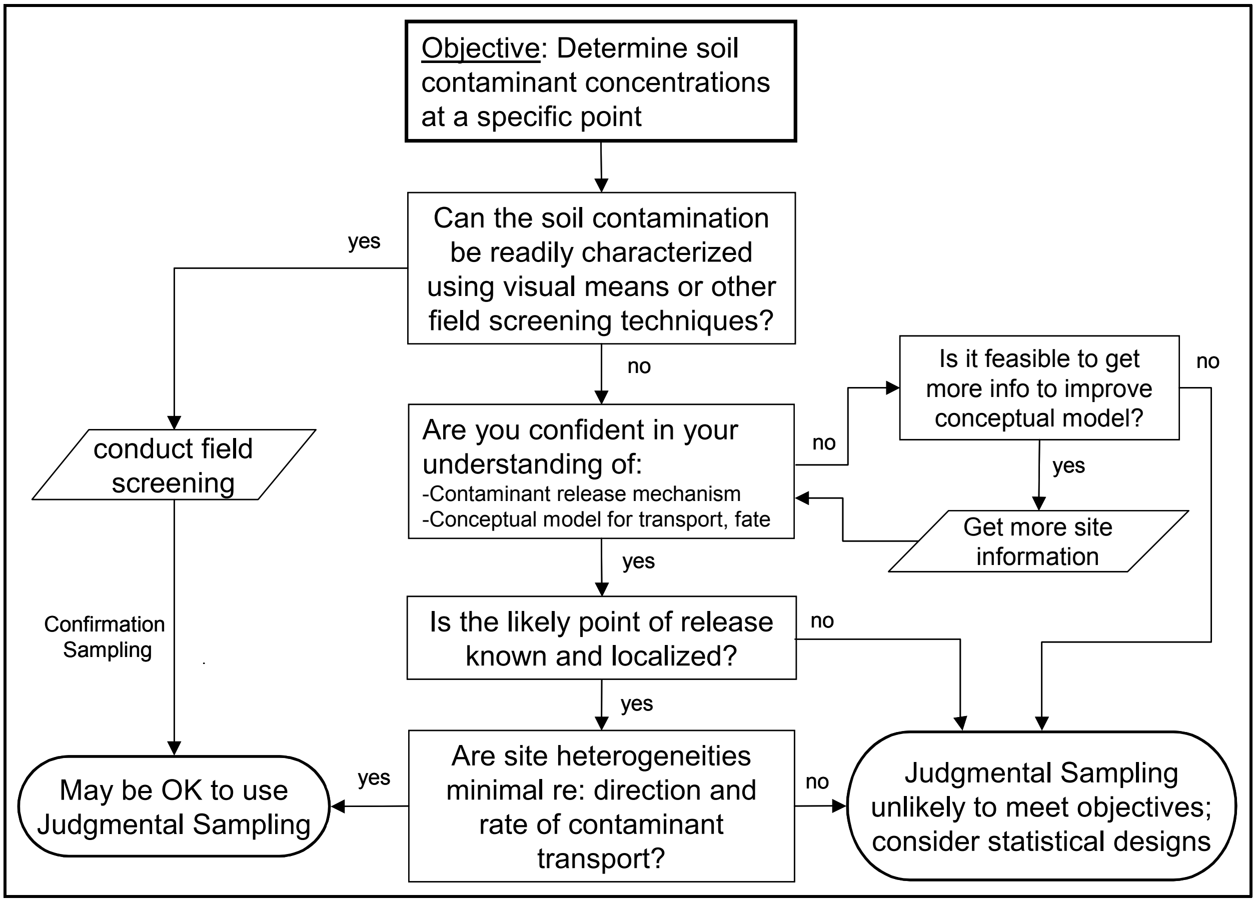

Figure 2. Decision process for determining whether judgmental sampling is appropriate for characterizing conditions at a suspect location or point.

appropriate. In the case of identifying and characterizing a point, a statistical approach would likely be a randomized grid search for the location of the point (otherwise known as "hot spot" sampling), which could be very expensive if the area of the "point" is small.

2.2.3 Characterizing a Soil Parameter over a Given Area

The decision process for determining whether judgmental sampling can be used to characterize a soil parameter over an area is shown in Figure 3. As indicated by the first branch in the process, using judgmental sampling to characterize soil contamination over an area is usually not appropriate because the objective is to characterize a parameter of a population, such as a mean contaminant concentration that will be used in a site-specific risk assessment. When attempting to draw conclusions about a population from a sample, one generally must rely on probability-based sampling to provide data that will support unbiased estimates and allow the calculation of statistical variance. While an argument can be made that an average can be appropriately estimated using judgmental sampling when the medium is known to be very homogeneous, this is rarely the case with soils, and one still is left with the problem of not being

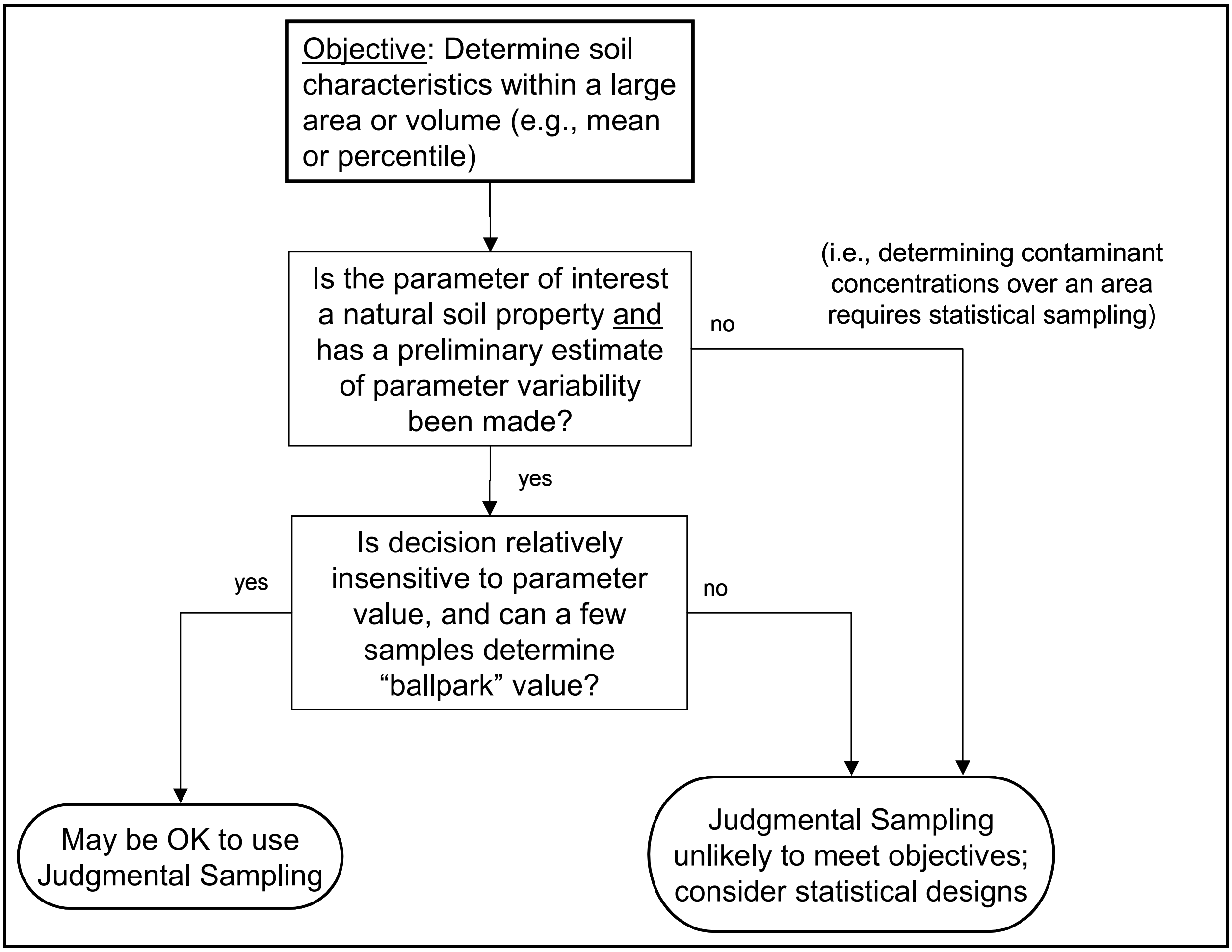

Figure 3. Decision process for determining whether judgmental sampling is appropriate for characterizing a soil parameter over an area.

able to calculate a statistical variance unless it can be assumed that the soil concentrations are randomly distributed over the study area. Nonetheless, this decision process does provide a path to judgmental sampling for the particular situation in which a soil parameter needs to be estimated. If a preliminary estimate of the range of parameter values is available (e.g., from the literature) and the uncertainty for this parameter can be allowed to remain very large because the calculation or decision is not highly sensitive to this parameter, then using judgmental sampling to establish a "ball-park" estimate for the soil parameter over this area may be acceptable.

2.2.4 Characterizing a Pattern of Soil Conditions

The decision process for determining whether judgmental sampling is appropriate for characterizing a pattern of soil conditions (e.g., to place concentration isopleth lines or delineate a boundary of contamination) is very similar to the process described in Section 2.1 for characterizing conditions at a point. This sampling objective would be needed, for example, in situations where the nature of contamination has been determined to exceed a threshold of acceptable risk, but additional information is needed to determine the extent of the contamination that exceeds a cleanup level. The decision process is shown in Figure 4. The first possible justification for using judgmental sampling is that the pattern can be identified visually or through a reliable field screening method so that the sample locations can be targeted reliably. In this case, it would not be efficient to apply a statistical design.

Next, the decision process focuses on whether the parameter of interest is a contaminant concentration or a natural soil parameter. Soil parameters often vary so widely across even small areas such that usually the most appropriate method for characterizing any patterns would be to use a randomized grid sample (i.e., a statistical design that is often called "systematic sampling"). Next, the decision process focuses on the question of the degree of knowledge that is available about the release and about the likely movement of the contaminant around the site (i.e., the conceptual model of the site). If these are well understood, then you may have sufficient confidence in where you expect the contamination to be. If the release mechanism and the conceptual model are not well understood, the "loop" to the right-hand side in the figure provides for the opportunity to gather more information to improve those understandings. If that is not possible and therefore a lot of uncertainty remains as to where the contamination is expected to be, a statistical design is recommended. However, if the release mechanism and the conceptual model of the contamination are well understood, judgmental sampling may be more efficient that statistical sampling to confirm the understanding of where the contamination is. (The determination of how well the conceptual model is understood, and whether that understanding is sufficient to justify judgmental sampling, is a critical one that deserves more detailed consideration.) Continuing, there are additional considerations about the degree of heterogeneity in site conditions and the information available to subdivide the site into strata that determine whether a judgmental sampling scheme may be appropriate.

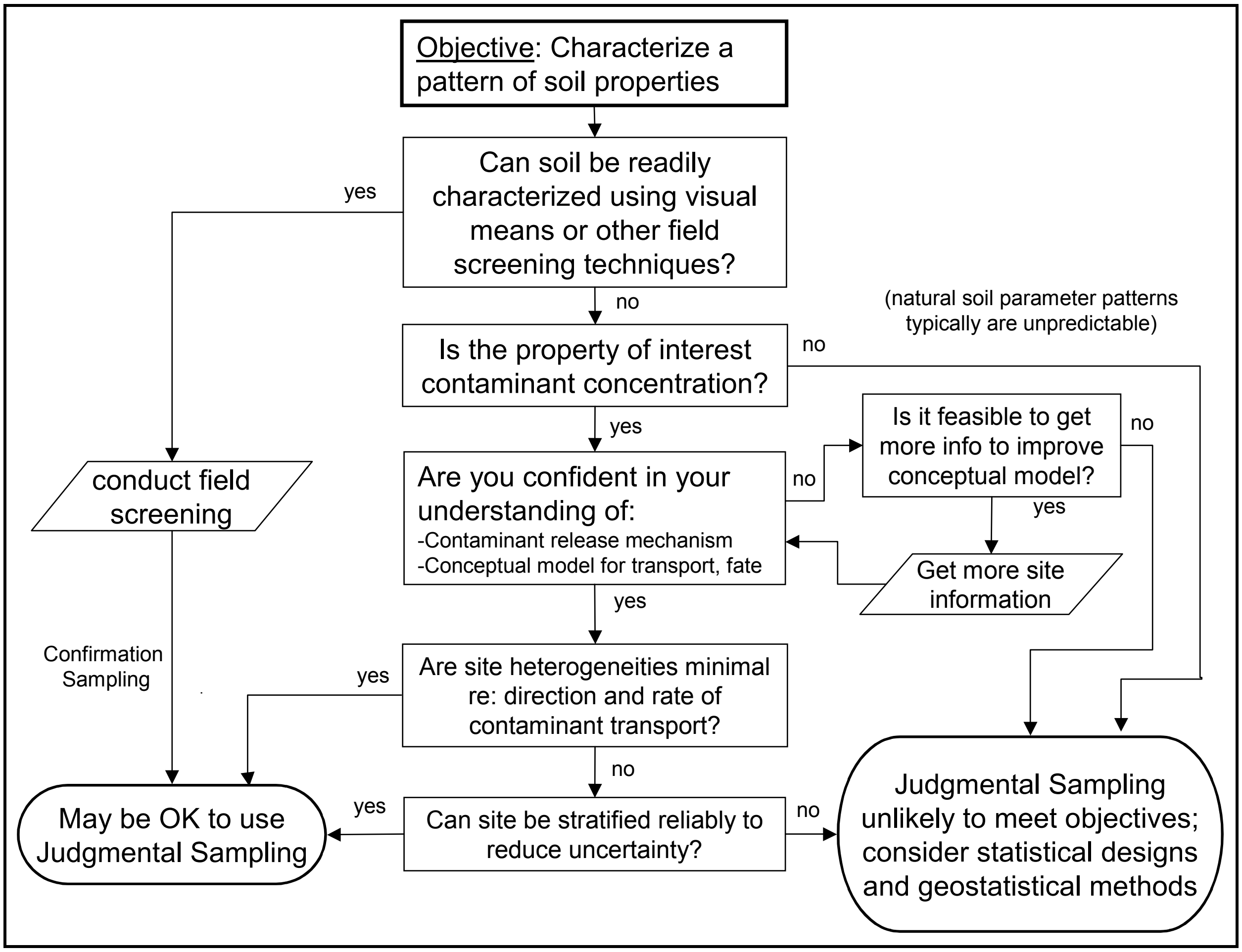

Figure 4. Decision process for determining whether judgmental sampling is appropriate for characterizing a pattern of soil conditions..

2.3 Specify Performance Criteria

If a statistical approach is selected, then DQO process Step 6 proceeds according to the activities in the DQO guidance. However, if a judgmental approach is selected, then the specification of tolerable limits on decision errors may not be a useful activity because the data typically will not support a statistical data quality assessment to determine whether the limits were satisfied. Instead, other performance criteria can be specified during Step 6, such as measurement quality objectives for the characterization of each sample (e.g., bias and precision acceptance criteria for laboratory analysis), and qualitative criteria that will help guide judgmental sampling in the field. Measurement quality objectives are particularly important when using a judgmental sampling approach because each sampling result may be used to make a decision about what actions to take, if any, in the area around that sampling location.[2] This localized point-by-point decision procedure places greater reliance on the representativeness of each field sample and accuracy of each measurement result.

2.4 Develop the Sampling and Analysis Plan

Once the sampling objectives are clear, the decision to use judgmental sampling has been made, and the performance criteria have been specified, the details of the judgmental sampling design can be developed and documented in the Sampling and Analysis Plan. Information from presampling activities or a preliminary investigation should provide crucial information to support the development of the plan, even if the project is in an early phase. The project manager should assign a qualified and experienced professional to develop and implement the plan. In particular, it is important to document the rationale behind the selection of sampling locations, taking into account the sampling objectives and intended use of the data. Where sampling locations can be determined in advance, they should be documented on a site map or conceptual model diagram. The plan also should address field contingencies, and the methods to be used to document the conditions and rationale underlying the selection of sampling locations in the field. When conducting screening to evaluate "worst case" locations, the rationale should address why the selected locations are believed to cover all of the worst case conditions, so that subsequent reviews of the results can address the likelihood that an important feature was missed. Many of the usual considerations regarding sampling and analysis methods, quality assurance and quality control protocols, and other technical requirements should be given special attention to ensure that they satisfy the demands of a decision procedure that is heavily dependent on the accuracy and reliability of each individual sampling result. If feasible, the draft plan should be peer reviewed by a qualified expert to strengthen the quality and defensibility of the approach.

3. CONSIDERATIONS WHEN USING JUDGMENTAL SAMPLING

This section addresses issues, considerations, and recommendations when judgmental sampling has been selected as the sampling approach. This discussion should not be viewed as exhaustive in scope or exclusive of other considerations. The very nature of judgmental sampling, with its reliance on expert knowledge applied to site-specific information, limits the depth to which the topic can be discussed in general terms.

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[2] See, for example, IDEM's RISC Technical Guide, Sections 3.4.4 and 6.3.1 (IDEM 2001)

3.1 Criteria for Reviewing Judgmental Sampling Plans

Systematic planning supports the defensibility of a judgmental sampling scheme and helps prevent it from devolving into haphazard sampling. As emphasized in section 2 above, systematic planning is an essential first step in developing any worthwhile sampling plan, whether judgmental or otherwise. The following points can be considered a checklist of criteria to be used when evaluating a judgmental sampling plan.

- Consistency with sampling objectives. The choice of judgmental sampling should make sense to other knowledgeable professionals. The target population should be clearly stated, along with the analytical characteristics and population parameters of interest, as applicable. If the choice is at odds with the principles outlined in this report, there ought to be a clear explanation why it is an exception.

- Documentation of rationale for selecting sampling locations. The project team, and the professional(s) making the judgments, must explain and defend their choices based on technical and logical criteria, including the number of samples taken. Documentation of the rationale underlying the selection of sampling locations instills discipline of thought and improves the transparency of assumptions.

- Adherence to correct sampling procedures. The strength of conclusions will depend more heavily on the integrity and representativeness of each sample, so it is important to ensure that the field sample collection methods are correct and reliable. See Pitard (1992) or Myers (1997) for descriptions of Gy's Theory of Sampling.

- Specification of correct analytical methods. The strength of results will also depend heavily on the appropriateness of the analytical methods used and the quality of their implementation. Verify that the performance of analytical methods are consistent with the objectives and known conditions, including potential interferences. This item should include the evaluation of quality assurance and quality control procedures.

- Accuracy and robustness of conceptual model. The defensibility of conclusions also rests on the quality of the underlying scientific understanding of contaminant release, transport, dispersion, transformation, fate, and uptake. To the extent that sensitive assumptions or model parameters can be verified by experiment or peer reviewed, a stronger case will be made that the conclusions are sound.

- Qualifications and experience of the professional making the judgments. Ultimately, the credibility of the judgments rests on the credibility of the professional(s) that make them. The educational qualifications, demonstrated experience, and past performance of the professional will be scrutinized if the results end up in court, so the planning team should consider this when assigning duties.

3.2 Criteria for Evaluating the Quality of Information Obtained Using Judgmental Sampling

The previous section looked prospectively at how to review plans for judgmental sampling; this section looks at the assessment phase, after judgmental sampling has been employed to obtain data and propose decisions or conclusions that may lead to actions. There is a need for much research in the area of combining data from multiple sources, including the combining of statistical sampling data and judgmental sampling data. At this time, the authors are not prepared to offer any recommendations in this area beyond the standard caveat: do not combine statistical sampling data with judgmental sampling data unless the approach has been developed under the guidance of a qualified statistician and passed a peer review. Typical statistical methods usually rely on the assumption of independent, identically distributed values of a random variable, and data obtained from judgmental sampling cannot be shown to satisfy that condition. Judgmental sampling data should not be ignored; they just need to be segregated and treated within the same framework of professional judgment and common sense.

The following items should be viewed as a checklist of considerations that are appropriate for reviewing in the beginning stages of a data quality assessment for judgmental sampling data.

- Were the qualifications and experience of the professional(s) who made the sampling judgments suitable for this project?
- Was the target population defined clearly and appropriately?
- Was the sampling approach consistent with the sampling objectives and intended use of the data?
- Was the rationale for the underlying choices of sampling locations and methods documented? If known, was the rationale logical and defensible?
- How well were the sampling and analysis methods implemented? What quality assurance and quality control records are available to support this assessment?
- Did the data validation process indicate that the acceptance criteria for field and laboratory bias and precision were met?
- How many professionals were used as judges? If more than one was used, how did they coordinate their work, and how well did their results agree?
- Are the data consistent with the conceptual site model used to formulate the sampling

plan?

- Does the variance of the data compare as expected with data collected previously at the site, or at similar sites?

- Do the conclusions seem reasonable and flow logically from the evidence? Taken as a whole, is the information coherent and consistent with the conclusions?

4. USING PROFESSIONAL JUDGMENT TO REDUCE THE COST OF STATISTICAL SAMPLING

As noted in several places, there are many situations where the appropriate sampling approach will involve statistical sampling. Concerns about the cost, complexity, and transparency of statistical sampling and the resulting data analysis are often well founded. However, many developments over recent years have made statistical sampling more cost effective, and easier to implement and understand. Research on sampling design methods that employ professional judgment has born some fruit; see the section below on Ranked Set Sampling. Computer hardware and software have evolved to the point where many previously unsolvable problems and impractical methods are now accessible via numerical simulation techniques. Also, a clear consensus has emerged within the scientific and statistical community regarding the sources of greatest uncertainty in environmental sampling, and practical tools and protocols have been developed to reduce that uncertainty to manageable levels. An excellent source of current practical statistical sampling methods can be found at the USEPA Quality Staff's web site (www.epa.gov/quality) in the form of *Guidance for Choosing Sampling Designs (EPA QA/G-5S)*[3].

4.1 Delineation of Boundaries for Stratified Sampling

The role of professional judgment in designing statistical sampling plans has always been acknowledged by statisticians. Perhaps one of the easiest and most fruitful approaches is to apply professional judgment in the delineation of boundaries for strata in stratified random sampling. By dividing the target population into subgroups that are more homogeneous within each group, more precise estimates of stratum means can be obtained due to the smaller statistical variance, and these stratum means can be combined to produce more efficient estimates of the total population means. "More efficient" means fewer samples to achieve a given performance goal, which translates to lower cost.

[3] Final version of the document is expected to be available in August 2002.

The authors believe that many current applications of judgmental sampling could be transformed into applications of stratified random sampling, sometimes with costs that are comparable to judgmental sampling. The elements of this approach would rely heavily on the use of professional judgment to delineate stratum boundaries using criteria similar in many respects to those used to select sampling locations under judgmental sampling. The professional may choose the stratum boundaries to be as small as necessary to satisfy the sampling objectives and his or her own concern about ensuring similarity (homogeneity) of conditions within the stratum. In essence, instead of selecting a specific point at which to sample, the professional would identify a bounded area around that point (the stratum) within which at least two or three random samples would be taken (so that a statistical variance within the stratum can be calculated from the data). The field sampling crew also would be required to record the area of each stratum, so that the resulting data can be weighted in proportion to the area of the stratum from which the data were generated. In larger strata, a randomized grid sampling scheme might be used to ensure broad coverage of the stratum area.

Using a traditional statistical sampling design approach, the number of samples within each stratum would be calculated based on the DQOs and estimates of variance within each stratum (see USEPA 2002c and *Guidance for Choosing Sampling Designs, EPA QA/G-5S,* when available). However, the planning team may be able to relax the performance criteria to allow smaller sample sizes if the budget constraints are severe and the decision maker is willing to tolerate higher decision error rates. Given that at least two or three samples per stratum would be taken under this scheme, whereas a judgmental sampling approach might call for only one sample per stratum, then clearly the cost of stratified random sampling will be higher than a corresponding judgmental approach, all other things equal. However, if the data can be used for multiple stages of a site investigation because they can be used in subsequent risk assessment calculations, there may be overall savings due to fewer sampling mobilizations.

Under certain conditions, composite sampling can be used to keep sampling and analysis costs under control. When the parameter of interest is a mean, and the contaminants and soil conditions allow for composite sampling (and there are no concerns about hot spots being "averaged away"), great savings often can be achieved by compositing within strata. Composite sampling gathers information from many more areas of the site than would otherwise be possible, and reduces the variance through "physical averaging." This reduces the number of samples that need to be analyzed to achieve a particular performance goal, which reduces costs.

4.2 Ranked Set Sampling

Ranked set sampling is a relatively new sampling design approach that explicitly employs a combination of randomization and professional judgment and/or screening measurement methods to improve the efficiency of estimates, sometimes dramatically. Ranked set sampling requires a relatively large number of potential samples to be identified in the field, yet only a small portion of them are actually taken and analyzed. The selection of samples to be analyzed uses a ranking scheme that can be based on quick field analytical methods, or the application of professional judgment based on some observable characteristics of the samples that agree (or correlate) with the level of contamination. The RISC Technical Guide (IDEM 2001) contains a good explanation of ranked set sampling in section 7.9.4.5, along with references for additional guidance.

4.3 Further Areas for Research

The expert panel considered a number of other areas that might, over time, yield practical techniques for reducing sampling and analysis costs while improving the quality of information available to support decision making. Currently these areas are either on the forefront of research, or require sophisticated methods and highly trained and skilled practitioners to ensure success.

Bayesian methods of inference and data analysis are important areas of research and practice in statistics and decision theory. Bayesian methods allow expert judgement to be encoded in probability distributions, which are then updated based on data and information gained through an investigation. Bayesian methods can be controversial, and the calculations can be very complex for large and realistic representations of problems. The expertise required to implement the methods, and the effort involved in conducting elicitations of subjective probabilities were determined to be inconsistent with the goal of practical, transparent methods that would be accepted by stakeholders and regulators. Nonetheless, some bibliographic references on Bayesian methods are provided in Appendix C for the reader interested in pursuing this line of inquiry further.

Geostatistical methods have come into much wider use in recent years, as the theory, practice, and tools have matured. Geostatistical methods use information about the spatial autocorrelation that exists for most environmental variables to develop maps that can represent contaminant concentration isopleths, block estimates of mean concentrations, uncertainty maps, and other summaries that can be used to support site decisions. Professional judgment is an important part of any geostatistical investigation. Myers (1997) and Isaaks and Srivastava (1989) provide good introductions with general references.

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USEPA. 2000b. *Data Quality Objectives Process for Hazardous Waste Site Investigations, EPA QA/G-4HW.* U.S. EPA Office of Environmental Information, Quality Staff, EPA/600/R-00/007.

USEPA. 2000c. *Guidance for Data Quality Assessment: Practical Methods for Data Analysis, EPA QA/G-9*. U.S. EPA Office of Environmental Information, Quality Staff, EPA/600/R-96/084.

USEPA. 2000d. *EPA Quality Manual for Environmental Programs*. U.S. EPA Office of Environmental Information, Quality Staff, 5360 A1.

Appendix A

Additional Background Information Comparing Judgmental and Statistical Sampling Approaches

This appendix contain additional discussion of the differences and tradeoffs between judgmental and statistical sampling.

Figure 1 illustrates how conclusions based on evidence from statistical sampling differ from conclusions supported by judgmental sampling. The figure assumes that the sampling objective is to make some inference about a target population, such as the surface soil at a site. The key distinction between the judgmental sampling path versus the statistical sampling path involves the degree to which professional judgment must be used to extrapolate results beyond the specific sample units (such as a soil sampling location). With judgmental sampling, any statements you make about conditions beyond the actual sample units that were measured would be based on extrapolations based on subjective judgments about how well your assumptions and conceptual model agree with actual conditions at the site. In soil and subsurface sampling, this means that the data can be used to support statements principally about the soil in the lab, but the strength of any conclusions drawn about the soil that is still back at the site are dependent on the accuracy and completeness of the expert's knowledge and judgment about the conceptual site model. It is still possible to make inferences about the overall conditions at a site, but these inferences usually require sophisticated methods to adjust confidence intervals to account for the non-random features of judgmental samples, and are almost always made with less accuracy and precision than can be obtained using a statistical sample. With a statistical sampling plan, the strength of conclusions you make about the sampled population can be supported in a clear and direct way by statistical sampling theory, which allows you to draw valid inferences about the sampled population and characterize the uncertainty associated with those inferences using standard, quantitative methods.

Some people may argue that judgmental sampling is the best approach when time and money are severely limited. If the sampling objective is consistent with the benefits and limitations of judgmental sampling, then this sampling approach may be appropriate. However, if the sampling objective cannot be met through judgmental sampling, then any time and resources spent collecting data that cannot be defensibly used for the intended purpose will be wasted. Moreover, there are many statistical sampling schemes that combine efficient methods with carefully focused professional judgments to yield highly cost-effective sampling and analysis plans. For example, professional judgment can be used to divide a site into sampling strata, within which random samples can be taken. The resulting stratified random sampling design will be more efficient than simple random sampling. If the

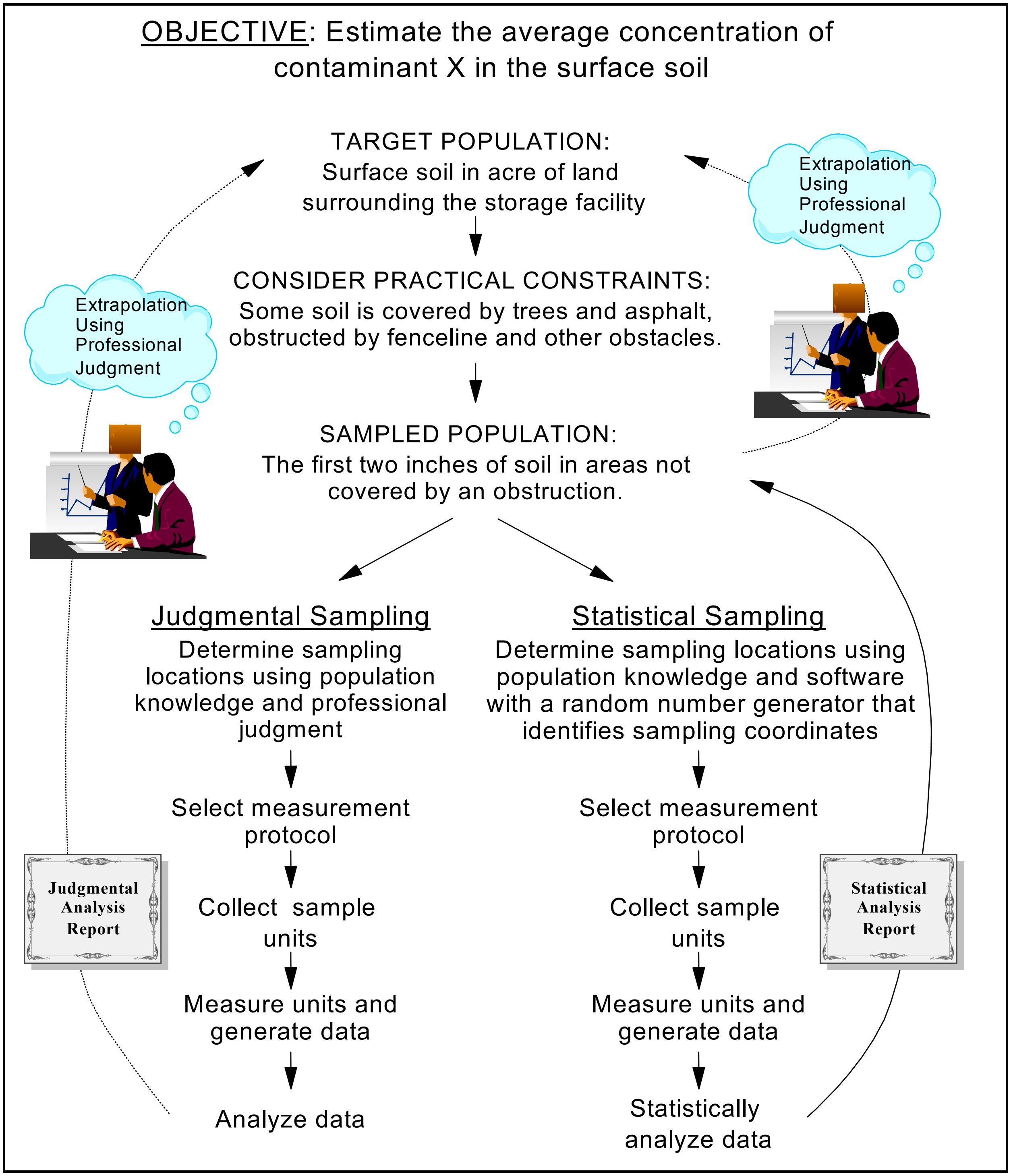

Figure A1. Inference from judgmental sampling requires greater reliance on the quality and extent of professional judgment used to extrapolate from the sampling results, as compared to statistical sampling.

One of the more critical aspects of any sampling design is determining the intended use of the resulting data. In particular, it must be clear whether site decisions will be made on a local, point-by-point basis, where the chemical analysis results of each individual sample determines the action to be taken at that sampling point; versus a more aggregate approach where the chemical analysis results from multiple samples over an area will be combined, mapped, or otherwise analyzed as a group to determine the action to be taken within that area. Point-by-point decision rules are often associated with judgmental sampling; decision rules that aggregate data are often associated with statistical sampling.

The type of data needed will depend on the objective of the site decision, which in turn will depend on the phase of the investigation. Early in the investigation, the objective may be to identify whether suspected contamination actually exists, and which contaminants are present. Another critical focus is the development of a conceptual site model of contaminant release, transport, dispersion, transformation, and uptake by living organisms. As the investigation proceeds, the focus turns to the extent of contamination, and whether the risk to human health and the environment is great enough to take action. If a decision is made to take some remedial action, then additional information about the volume of soil to be treated or removed must be obtained, and perhaps other characteristics studied to support the design of the cleanup methods. Once a cleanup approach has been selected, data are often needed to monitor the effectiveness of the cleanup process. Eventually, the objective may be to decide whether the cleanup is complete and the site can be cleared for subsequent use, perhaps with restrictions. The DQO process helps the project team clarify the types of decisions that need to be supported by environmental data at various stages of the site life cycle. This allows the team to streamline the overall process by anticipating future data needs and combining data operations where possible. The caveat here is that data collected for one purpose early in the life cycle may not serve the objective of a later decision. For example, judgmental sampling done early in the life cycle to verify that a contaminant was released is not likely to produce data that can be used for an estimate of average contaminant concentrations needed for a site-specific risk assessment.

The choice of a sampling approach is important not only because of the decisions at stake, but also because the collection of accurate environmental measurement data is expensive. Mobilization of a sampling crew can involve the assignment of multiple technicians and engineers over days or weeks, depending on the scale and complexity of the investigation. A single laboratory analysis of a soil sample can cost several hundred dollars or more. Therefore, the number of samples needed to support decision making at a site can be a major influence on the cost of the site investigation. Moreover, the overall objective usually is to reduce risk to an acceptable level while using limited resources efficiently. Whether the investigation and cleanup is funded by a private entity or the government, a responsible project manager will seek to maintain a balance between the desire to reduce uncertainty by collecting and analyzing more data, and the desire to move quickly to the cleanup stage where tangible risk reduction actions are to be taken. The DQO process provides performance criteria by which a "stopping rule" can be formulated to prevent unnecessary sampling and analysis.

Uncertainty in environmental measurements is unavoidable, so the issue for the site investigation team is to reduce uncertainty to a level that is tolerable to the decision maker. This translates to providing the optimal amount of sufficiently accurate and reliable information to support decision making at each stage of the site management life cycle. Deciding whether the quantity of information is "optimal" and whether the quality of that information is "sufficiently accurate and reliable" is not a simple matter. Subjective value judgments are unavoidable when specifying how much uncertainty is acceptable for a given decision. Nonetheless, the decision process can be supported by objective assessments of how the quantity and quality of data affects decision making, based on well-established scientific, engineering, and statistical knowledge. The USEPA's systematic planning and data quality assessment methods and tools can help project teams gain agreement on how much uncertainty can be tolerated, and what type, quality, and quantity of data are needed to support decision making with the desired level of confidence in the results (see USEPA 2000a, USEPA 2000b, and USEPA 2000c). TheDQO process is useful whenever the collection of environmental data is being considered at any stage of the site management life cycle, regardless of whether judgmental or statistical sampling is being considered. However, some of the benefits of the DQO process may be limited when judgmental sampling is used, because the resulting data may not allow a valid quantitative assessment of uncertainty, which is required if the tolerable levels of uncertainty are to be used as criteria for deciding when the quality and quantity of data are sufficient for the decision.

Appendix B

Literature Search Results

RTI conducted a literature search using the terms "judgmental sampling," "expert judgment," "authoritative sampling," and "biased sampling." The following citations are the relevant results.

DuBois, David W; Watson, John G; Chow, Judith C; Green, Mark; Frank, Neil; Pitchford, Marc. "PM sub(2.5) monitoring network design strategies." Desert Research Inst, Reno, NV, USA
The 1998 91st Annual Meeting & Exposition of the Air & Waste Management Association, San Diego, CA, USA, 06/14-18/98
SO: PROC A WASTE MANAGE ASSOC ANNU MEET EXHIB, AIR & WASTE MANAGEMENT ASSOC, PITTSBURGH, PA, (USA), 1998, 10ppp,
PB: AIR & WASTE MANAGEMENT ASSOC, PITTSBURGH, PA, (USA)
AB: In response to the U.S. EPA National Ambient Air Quality Standards for PM sub(2.5),, a new network of PM sub(2.5) monitors will be required throughout the nation. The PM sub(2.5) monitoring network will represent population or community exposure where people live, work and play. These do not necessarily correspond to the locations of maximum concentrations in an area. The network of PM sub(2.5) monitors will likely approach 1,500 in number as the implementation gets underway. PM sub(2.5) monitors are to be located at specific sites that represent neighborhood or urban scales to determine compliance with standards. Transport and background sites are located between, and away from, planning areas to determine regional increments to PM measured around the planning area. Network design philosophies examined in this paper include random, systematic, judgmental sampling, combined judgmental/systematic sampling and other analytical model based sampling techniques. Methods to determine the information content of different monitors were also evaluated.

TI: Incorporating expert judgement into statistical sampling designs for contaminated sites
AU: Ferguson, C; Abbachi, A
SO: Land Contam. Reclam., Vol. 1, No. 3, pp. 135-142 (Jul. 1993)
AB: Sampling designs for contaminated sites need to reflect the complexities of site assessment and the wide variations in prior information that may be available to the site assessor (expert). This paper reviews some basic principles of spatial sampling and shows how sampling strategies for detecting contaminant hot spots can be modified to reflect the expert's knowledge of the site and strength of belief that hot spots exist, or are located in particular sub-areas of the site. It also describes how multi-stage sampling can be used to increase the probability of detecting hot spots, and to characterize contaminant spatial distribution using geostatistical methods. The latter is particularly important if the aim of remedial design is to minimize direct human exposure to contaminants.

TI: Cost effective sampling - a statistical approach
AU: Ferguson, C
AV: Full proceedings from International Business Communications Ltd., IBC House, Vickers Drive, Brooklands Industrial Park, Weybridge, Surrey KT13 0XS, UK. Price #90.00
SO: Paper from Proc. Int. Conf. on Site Investigations for Contaminated Sites, held London, UK, 21-22 Sep. 1992. IBC Technical Services Ltd., (1992). 13pp.
AB: A properly formulated sampling strategy should be a key component in any contaminated site investigation. This paper reviews the design principles for effective spatial sampling to achieve the major objectives of a site assessment. The number of sampling points needed to achieve a given probability of success in locating a hot-spot

(critically contaminated area) will depend on the sampling pattern chosen and the hot-spot size and shape. Designs can be improved by varying sampling density to reflect expert judgement. Multi-stage sampling schemes can also prove very cost-effective.

DIALOG(R)File 40:Enviroline(R)
00405904 ENVIROLINE NUMBER: 93-01837
Risk Estimation and Expert Judgment : the Case of Yucca Mountain
Shrader-Frechette, Kristin, Univ of South Florida, Tampa
Risk: Issues Health Saf v3, n4, p283(33)
Fall 92
JOURNAL ANNOUNCEMENT: 19930200
DOCUMENT TYPE: journal article LANGUAGE: English
(Full text available from Congressional Information Service at
1-800-227-2477.)
ABSTRACT: Controversy surrounds the use of expert judgment by DOE to estimate potential risks at Yucca Mountain, NV, a candidate radioactive waste repository site. Four classes of expert judgments used in Yucca Mountain risk assessments are critiqued. These judgments claim that: short-term studies offer an adequate basis for extrapolating to long-term risks, models of site hydrogeology are reliable even though they have not been confirmed in the field; simplifications of site hydrogeology do not misrepresent actual conditions; and sampling of site characteristics is extensive enough to provide a basis for predicting behavior at the site. The last three judgments are examples of faulty science and argue for greater conservatism in Yucca Mountain studies.
SPECIAL FEATURES: 117 reference(s)
MAJOR DESCRIPTORS: NEVADA TEST SITE; ENV EXPERTS; RISK ASSESSMENT;
RADIOACTIVE WASTE DISPOSAL; WASTE DISPOSAL, SUBSURFACE; DISPOSAL SITES;
US DEPARTMENT OF ENERGY; RADIATION PROTECTION
MINOR DESCRIPTORS: GROUNDWATER; POLLUTANT FATE; POLLUTION FORECASTING
REVIEW CLASSIFICATION: 14

DIALOG(R)File 292:GEOBASE(TM)
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00898185 SUPPLIER NO. 2175526
U.S. EPA computer system for simulating site characterization activities at
Superfund cleanup sites
Naber S.J.; Buxton B.E.; Bertoni M.J.; Scheibe T.D.; Warren J.
ADDRESS: S.J. Naber, Battelle Memorial Inst., 505 King Avenue, Columbus OH
43201, United States
EDITOR(S): Baafi E. Y.; Schofield N. A.
Geostatistics Wollongong 96 - Proceedings of the Fifth International
Geostatistics Congress, Wollongong, Australia, September 1996,
(1066-1074), 1999
COUNTRY OF PUBLICATION: Australia
ISBN: 0792344944
PUBLISHER: Kluwer Academic Publishers

DOCUMENT TYPE: Book; Article
LANGUAGES: English
This paper describes the capabilities of a new computer system which the U.S. Environmental Protection Agency (EPA) Office of Research and Development is developing to simulate field sampling and statistical analysis to characterize the level and spatial distribution of environmental contamination at a Superfund cleanup site. This system makes use of different geostatistical methods for simulating a wide variety of contamination in groundwater and soil. It also includes different algorithms for sampling the resulting contamination, as well as the EPA geostatistical software, Geo-EAS, for analysis of the sampling results. The contamination can be sampled with a variety of field designs including simple random sampling, stratified random sampling, gridded sampling, phased sequential sampling, and judgmental sampling . The system also includes means for assessing the statistical performance of the design and data analysis methods by comparing the simulated study results to the underlying true database. The entire package is organized into a menu-driven, PC-based, geographic information system which allows easy use and effective display of results. A variety of uses are envisioned for this new EPA computer system. Perhaps three of the most important for the geostatistical technical community are: (1) it provides a diverse set of conditions for testing the statistical properties of any number of existing or proposed new sampling designs, (2) it provides a similar setting for testing the properties of various geostatistical data analysis methods, and (3) it provides a powerful tool for teaching the proper steps of a geostatistical site characterization from sampling design all the way through the final presentation of statistical analysis results.
DESCRIPTORS:
Superfund; conference proceedings; contaminated land; geostatistics; remediation
GEOGRAPHIC DESCRIPTORS:
United States
CLASSIFICATION CODE AND DESCRIPTION:
72.14.1 (Reclamation and conservation)
RECORD HISTORY:
COMPLETED RECORD - July 24, 1999

DIALOG(R)File 292:GEOBASE(TM)

00643034 SUPPLIER NO. 1058309
Ranked set sampling for vegetation research
Johnson G.D.; Patil G.P.; Sinha A.K.
ADDRESS: Dept of Statistics, Pennsylvania State Univ, University Park, PA, USA
Abstracta Botanica, 17/1-2 (87-102), 1993
DOCUMENT TYPE: Journal
LANGUAGES: English
Estimates of mean values of forest, grassland or other vegetation resources

may be obtained with greater precision than other common sampling techniques by using ranked set sampling . This works by maintaining the unbiasedness of random sampling while increasing the changes of representing the full range of the underlying population by capitalizing on expert judgment or quantitative information about the population at the sample level. -from Authors
DESCRIPTORS:
vegetation analysis; sampling ; ranked set sampling
CLASSIFICATION CODE AND DESCRIPTION:
73.5 (GENERAL MICROBIAL ECOLOGY)
RECORD HISTORY:
COMPLETED RECORD - January 1, 1995

"BIASED SAMPLING" SEARCH

Demirhan M, Ozdamar L. "Integrating expert knowledge in environmental site characterization." IEEE Transactions On Systems Man And Cybernetics Part C-Applications And Reviews 31 (3): 344-351 AUG 2001
The site characterization issue is the most essential task to be undertaken prior to the reclamation of a potentially contaminated site and it is composed of sampling, laboratory analysis, and data evaluation phases. We are primarily concerned with the data evaluation phase and we utilize a recently developed adaptive areal partitioning algorithm to characterize the site. Here, we
enhance this approach by integrating expert knowledge (expert belief) into the fuzzy areal assessment scheme which derives information from sample data. We propose to allocate an adaptive weight to expert belief during the assessment. We compare the belief-integrated approach with the nonintegrated one on synthetically generated sites where both uniform and biased sampling have been applied independently. In biased sampling, the zones claimed to be highly contaminated (by the expert) are allocated a higher sampling density. We demonstrate that the belief-integrated approach outperforms the nonintegrated one both when the expert is correct or mistaken in his/her judgment irrespective of the sampling methodology.

Mahfoud,M.; Patil,G.P. "Size-biased sampling, weighted distributions, and Bayesian estimation." Statistics In Theory And Practice : Essays In Honour Of Bertil Matern edited by Bo Ranneby. Umea, Sweden : Swedish University of Agricultural Sciences, Section of Forest Biometry, 1982. p. 173-187.
NO ABSTRACT

Stephen E. Silliman; Brian Berkowitz. "The Impact of Biased Sampling on the Estimation of the Semivariogram Within Fractured Media Containing Multiple Fracture Sets." Mathematical Geology 7/1/00, Vol 32 (Number 5), p543-560
Abstract: Monte Carlo simulation was used to examine the error (statistical bias) introduced in estimating a sample semivariogram through application of oriented sampling patterns to variables which are correlated with fracture orientation. Sample semivariograms of the directional components of the water velocity were used to illustrate that oriented sampling schemes can provide biased data sets which result in error in the estimation of the semivariogram, particularly in the estimation of the sill (or variance). Three sampling patterns were used to analyze directional semivariograms of the components of the fluid velocity: sampling along lines parallel to the mean regional hydraulic gradient, sampling among lines perpendicular to the mean regional hydraulic gradient, and sampling along fracture segments. The first two sampling patterns were shown to introduce substantial error in the sills of the velocity variograms. It is argued that this error is due to the combination of unequal sampling of fractures with different orientations (i.e., sampling bias) and the systematic variation in the magnitude of the velocity components with orientation of the fracture. As a consequence, it is suggested that correction factors developed to correct

fracture frequency statistics need to be extended to improve estimation of spatial moments of variables which are correlated with fracture orientation.

C. Nowell, M.A. Evans, L. McDonald. "Length-Biased Sampling in Contingent Valuation Studies." Land Economics Nov88, Vol. 64 Issue 4, p367-371
Abstract: Research examines the use contingent valuation of environmental commodities and the estimation of parameters associated with the utilization of a site over a specific interval of time. The variables of interest can include willingness to pay, length of visit, and expenditures associated with an activity. Techniques were presented that will adjust for the use of a simple mean for an estimate of a variable so that there is an unbiased estimate in the results.

Wolf U. Blackenhorn; Max Reuter; Paul I. Ward; Andrew D. Barbour. "Correcting for sampling bias in quantitative measures of selection when fitness is discrete." Evolution, Feb 1999 v53 i1 p286(6)
Abstract: A simple method for statistical correction in cases when sampling is biased is presented. The correction method is derived and its application is described. Its use is demonstrated with a simulation that proves that biased sampling does lead to inaccurate estimates of selection coefficients. This correction method is particularly useful in the analysis of the practical aspects of selection measurement.

Richard Bradley; Tess Durden; Nigel Spencer. "The creative use of bias in field survey." Antiquity, June 1994 v68 n259 p343(4)
AB: Archeologists tend to discover sites and artifacts under the influence of a set of expectations. Biases may be responsible for the manner in which some groups or individual researchers encounter only certain types of artifacts or sites while others find other types. A biased sampling method can be applied in field work using separate groups working under different biases to accomplish a thorough investigation of the site.

Schweigert, JF; Haegele, CW; Stocker, M. "Optimizing sampling design for herring spawn surveys in the Strait of Georgia, B.C." Canadian Journal of Fisheries and Aquatic Sciences [CAN. J. FISH. AQUAT. SCI.], vol. 42, no. 11, pp. 1806-1814, 1985
AB: Three estimators for two-stage sampling designs assuming unequal sized primaries (transects) were compared. The ratio estimator was found to provide the most consistent estimates of the mean and variance and so was used for estimating optimal sample design. Preliminary results from some biased sampling during 1976 and 1978 provided guidelines for the 1981 study designed to derive an optimal sampling design. Inconsistent results from the two areas surveyed during 1981 prevented general conclusions, but a corroborating resurvey of one area in 1983 suggested that a sampling intensity of five samples per 100 m of transect and transects every 250-400 m along the length of the spawn should result in estimates of the mean egg density with a standard error no greater than 25%. Systematic sampling is longistically preferable to random sampling and can be incorporated into the two-stage design described herein which should be used in future spawn surveys designed to estimate spawning escapement.

O'-Hara-AJ; Faaland-BH; Bare-BB. "Spatially constrained timber harvest scheduling." Canadian-Journal-of-Forest-Research. 1989, 19: 6, 715-724; 29 ref.
AB: Multiple-use management of forests often requires imposition of spatial constraints on the selection of units for harvest. To satisfy such constraints, harvest units must be treated as integral units. A biased sampling search technique (SCRAM - spatially constrained resource allocation model) was used to find integer solutions to operationally sized problems. Solutions found for the sample problems were within 8% of the upper bound of the corresponding linear programming solution and less than 4% below the upper bound on the true optimum as defined

by a confidence interval estimator.

Theriot, E "Taxon sampling and stability of phylogenetic hypotheses, using samples from the algae.
Journal of Phycology [J. PHYCOL.], vol. 25, no. 2 suppl., p. 5, 1989
AB: There are two types of accuracy in representing phylogenetic relationships as branching diagrams. The accuracy with which a branching diagram represents the branching order of the true phylogeny can probably only be known in the case of experimentally reared organisms. However, the accuracy with which the branching diagram orders the data set at hand according to some model or convention can be investigated. Jackknife and purposefully biased sampling strategies were applied in experiments on algal data sets, including diatoms and green algae, using both molecular and morphological data, to demonstrate the importance of taxon sampling. Tree stability was found to be a function of amount and distribution of homoplasy. The fossil record is significant because it provides a more complete sample of taxa. Molecular and morphological data are equally susceptible or robust to errors induced by sampling.

Helz, GR; Setlock, GH; Sinex, SA. "210-Lead geochemistry in Chesapeake Bay: The representative sampling problem." Estuaries, vol. 4, no. 3, pp. 271-272, 1981
AB: For deposition rate measurements, 17 cores were selected, based on x-ray evidence of minimal bioturbation, from a group of more than 50 collected during the Chesapeake Bay Program (EPA). Measured deposition rates ranged from 0.7 to 17.8 mm per yr and averaged 5.9 mm per yr. The rates vary irregularly, rather than systematically, along the Bay's axis, but the highest values (> 10 mm per yr) all occur in the middle section where geochemical balance calculations require that the average deposition rate be 0 plus or minus 2 mm per yr. Some high rates were independently confirmed. The measured rates are problematical, because if correct and representative, they imply that sediment deposition exceeds known sediment inputs by roughly fivefold. This problem is concluded to arise from biased sampling necessarily inherent in obtaining material for 210-Pb geochronology. Coring is less successful in sandy, high energy terranes (where deposition rates are often small or even negative) than in muddy, quiescent terranes (where high deposition rates are more likely). X-ray searches for undisturbed cores add fur ther bias. Thus while 210-Pb deposition rates may be valid for specific sites they tend to over estimate regional deposition.

PATIL GP. "ENCOUNTERED DATA, STATISTICAL ECOLOGY, ENVIRONMENTAL STATISTICS, AND WEIGHTED DISTRIBUTION METHODS." ENVIRONMETRICS 2 (4): 377-415 DEC 1991
Abstract: We have begun to experience in data gathering and analysis in modern ecological and environmental work a space age/stone age syndrome. Also we are challenged to break into the cycle of no information, new information, and non-information while dealing with soft data, hard looks, and prudent decision-making involving errors of the 'third' and the 'fourth' kind in addition to
those of the first and the second type. Weighted distribution methods arise in the context of data gathering, modeling, inference, and computing, and help provide a unified approach in dealing with encountered data.

PATIL GP, RAO CR. "WEIGHTED DISTRIBUTIONS AND SIZE-BIASED SAMPLING WITH APPLICATIONS TO WILDLIFE POPULATIONS AND HUMAN FAMILIES." BIOMETRICS 34 (2): 179-189 1978
NO ABSTRACT

DIALOG(R)File 103:Energy SciTec

04261674 EDB-98-022089
Title: Sampling approach for characterization of the Scarboro Community, Oak Ridge, Tennessee
Corporate Source: Jacobs Engineering Group, Inc., Oak Ridge, TN (United States) (Code: 9532967)
US DOE Project/NonDOE Project: P
Country of Origin: United States
Country of Publication: United States
Abstract: The Scarboro Community is a small urban community in the city of Oak Ridge, Tennessee. It is located approximately 457 m northwest of the Oak Ridge Y-12 Plant along the US Department of Energy (DOE) Oak Ridge Reservation (ORR) boundary. The purpose of this investigation is to validate measurements taken at the perimeter air monitor 46 (located in the Scarboro Community) and external gamma data collected during past flyover surveys. Five sampling tasks will be performed to validate these measurements. These tasks include biased sampling of residential properties, random sampling of residential properties, ORR boundary sampling, focused soil sampling in the Scarboro saddle, and surface water and sediment sampling in the Scarboro tributaries. Additionally, a radiological walkover of representative areas of the Scarboro Community will be performed. The two contaminants of concern are mercury and radionuclides.

DIALOG(R)File 103:Energy SciTec

03680723 EDB-94-096689
Title: Gulf Coast sediment organic contaminant distribution: Results from the EPA EMAP-NC program
Author(s): Wade, T.L.; Brooks, J.M.; Jackson, T.J.; Wong, J.M.; Denoux, G.J.; Fay, R.R. (Geochemical and Environmental Research Group, College Station, TX (United States)); Summers, J.K.; Macauley, J.M.; Heitmuller, P.T. (EPA, Gulf Breeze, FL (United States))
Title: Ecological risk assessment: Lessons learned
Conference Title: 14. annual meeting of the Society of Environmental Toxicology and Chemistry (SETAC)
Conference Location: Houston, TX (United States) Conference Date: 14-18 Nov 1993
Publisher: Pensacola, FL (United States) Society of Environmental Toxicology and Chemistry
Publication Date: 1993 p 168 (356 p)
Report Number(s): CONF-931152--
Document Type: Analytic of a Book; Conference Literature
Language: English
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Abstract: The Environmental Protection Agency (EPA) designed the Environmental Monitoring and Assessment Program-Near Coast (EMAP-NC) to provide a quantitative assessment of the extent of coastal environmental problems by measuring the status and changes in selected indicators of ecological conditions. Concentrations of organic contaminants including polycyclic aromatic hydrocarbons (PAH), chlorinated pesticides, tributyltin, and polychlorinated biphenyls (PCB) were determined in over 300 sediment samples collected in 1991 and 1992. The EMAP-NC program utilizes a probability-based sampling design in order to provide an unbiased, statistically valid estimate of contaminant concentrations. This estimate can be expanded, with quantifiable confidence, to the entire Gulf Coast. Most of the organic contaminant concentrations found were low compared to concentrations reported in the literature from biased sampling near point sources of input. Many of the contaminants provide a more skewed distribution because many analytical results are below the method detection limit. Preliminary analyses

indicate that a probability-based database has been produced. Conclusions regarding extents of organic contamination of the Gulf Coast and use of the EMAP approach will be discussed.

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Title: Risk assessment in populations screened for cancer
Author(s): Walter, S.D. (McMaster Univ., Ontario); Day, N.E.; Prentice, R.L.; Whittemore, A.S. (eds.)
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Conference Title: SIMS conference - environmental epidemiology: risk assessment
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Abstract: Expressions are derived for the anticipated prevalence of pre-clinical chronic disease in a population which is screened several times, and for the anticipated incidence of clinical disease during the inter-screening intervals. Using these expressions in conjunction with data routinely available from screening programs, one may estimate: the distribution of the duration of the preclinical disease phase, the distribution of lead times of prevalent cases of disease identified by the screen; the program lead time distribution; the screening sensitivity; and the underlying incidence rate in the population. Predictions may also be made of the risk of disease occurring in a given interval following any particular sequence of screening times, thus allowing alternative screening strategies to be considered. The survival experience of prevalent and incident cases may be compared, adjusting for lead time and length- biased sampling effects. An example is given using data from a breast cancer screening program.;

DIALOG(R)File 292:GEOBASE(TM)

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Designing surveys of forest diversity using statistical sampling principles
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EDITOR(S): Kohl M.; Gertner G.Z.
Caring for the forest: research in a changing world. Statistics, mathematics and computers. Proc. International Union of Forestry Research Organizations S4.11-00, Tampere, 1995, (117-143), 1996
LANGUAGES: English
Monitoring to detect changes in forest biodiversity requires that the data 1) actually reflect spatial and temporal patterns in biodiversity that are of interest, 2) are reliable and repeatable, and 3) use resources (time, money) optimally. Many sources of bias and variability exist that may confound temporal and spatial comparisons of biodiversity measures, even if the field sampling is identical at all locations (eg forest biodiversity

plots). In particular, measures such as presence/absence, species richness, relative abundance, and diversity indices are sensitive to 1) unequal sampling probabilities among species; 2) low probability of sampling rate species; 3) biased sampling ; and 4) spatially or temporally heterogeneous sampling. Standardized field methods and the use of techniques such as species-area relationships are not robust to the above.

These problems can be ameliorated through proper definition of a target population, judicious choice of a sampling frame and method for selecting sampling units, and collection of ancillary data to estimate and adjust for sampling heterogeneity.

Appendix C

Bayesian Modeling Papers/Bayesian Methods/Ground Water Monitoring

M.J. Small

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